MODULAR MANUFACTURING OF HONEYCOMB-REINFORCED CHARRING ABLATOR SYSTEMS FOR THE AEROSHELLS OF LARGE EDL VEHICLES

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ABSTRACT

Polymer-based charring ablator heatshields are made more robust by the use of honeycomb (H/C) reinforcement. For large EDL vehicles of 4.0-m and greater (and especially for the high-mass vehicles planned for manned exploration of Mars), heatshield production by direct H/C packing on vehicle aeroshells poses numerous and significant challenges. These challenges are overcome by the use of modular manufacturing, where pre-packed and precision-milled ablator units are secondarily bonded to vehicle structures. Producibility is enhanced, common manufacturing risks are mitigated, and costs are lowered. This paper discusses modular manufacturing techniques for EDL heatshields developed at the Ablatives Laboratory. Modular units were produced and evaluated and the advantages of modular manufacturing are reviewed.

1. INTRODUCTION

This paper discusses modular heatshield manufacturing for entry, descent and landing (EDL) vehicles, where the modules are ablator material that is reinforced with composite honeycomb (H/C). The modules are made from polymer-based charring ablators whose mixed compounds are moldable and packable. A heatshield of this type has not been flown (or produced) to date on a NASA mission. While recent projects have investigated aeroshells with modular heatshields, these were made of PICA material and were not honeycomb reinforced. Rather, they were shaped modules milled from monolithic slabs of formed PICA. This is because PICA has characteristics similar to a lightweight ceramic and is not moldable or packable. (The MSL Mars entry in 2012 will use a modular PICA system for aeroshell thermal protection.)

The Ablatives Laboratory (ABL) is developing processes and producing for the first time modular, honeycomb-reinforced ablative heatshield units for NASA as a new technology for future missions. Under sponsorship of NASA's In-Space Propulsion Technology program, we have produced two small 1.0-m diameter phenolic units to date and we are completing a larger 2.65-m silicone unit in 2011. Because there is a "learning curve" with regard to how to make such modular heat-shields, the smaller units were a necessary precursor to attempting a larger unit. Fig. 1 shows our engineering model for the designed configuration and assembly of a 1.0-m unit of 70-deg. half-cone angle. It consists of four flank modules and one nose module. Both the flank modules and the nose module have a surface area of about 2.0 ft^2. (0.19 m^2) Between flank modules, the seams are orientated at 18.0-deg off streamlines for a vehicle with zero AOA flight attitude. The gap filler of these seams is the same mixed ablator compound as the modules.

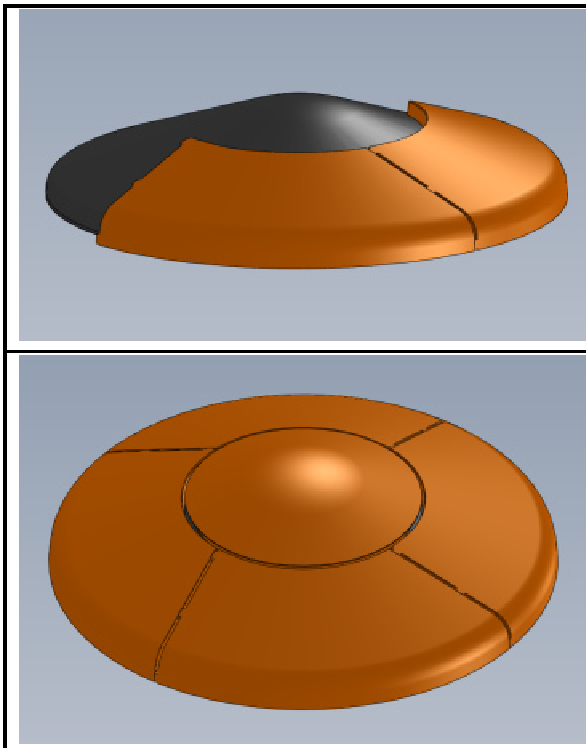

Fig. 1 – Modular Manufacturing 1.0-m Heatshield

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2. NEED FOR MODULAR PRODUCTION

Because they are small, heatshields on the aeroshells of 1.0-m size EDL vehicles are relatively easy to produce by a single operation of honeycomb packing, yielding a monolithic unit. But H/C packing is an inherently labor intensive process with stringent timelines due to resin pot life, solvent evaporation and other considerations. Making a monolithic, H/C-packed ablative heatshield for a large aeroshell of 4.0-m or 5.0-m diameter and greater becomes a very difficult manufacturing operation. And there are other factors that can make the monolithic approach more difficult and less suitable. These are: 1) thicker heatshields that require the packing of more ablator; 2) denser heatshields that also require more ablator, but greater packing effort in addition; and 3) polymer resin types whose mixed compounds are less "lubricious."

As background, Figs. 1-3 show photos of the standard ABL manufacturing process to produce a small monolithic heatshield of H/C-packed ablator. This is a 1.0-m diameter unit and the ablator was a silicone material of 20.0 lb/ft^3 with a 1.0-in. final thickness. In the top of Fig. 2, the large sheet of honeycomb composite is assembled from smaller panels that are joined together. In the bottom of Fig. 2, H/C is bonded to the aeroshell structure with film adhesive and oven curing is done under vacuum bag pressure. In Fig. 3, the left side shows the bonded honeycomb ready for ablator compound application. Shown In the right side is the finished ablator that has been packed, cured, and milled to final shape and thickness.

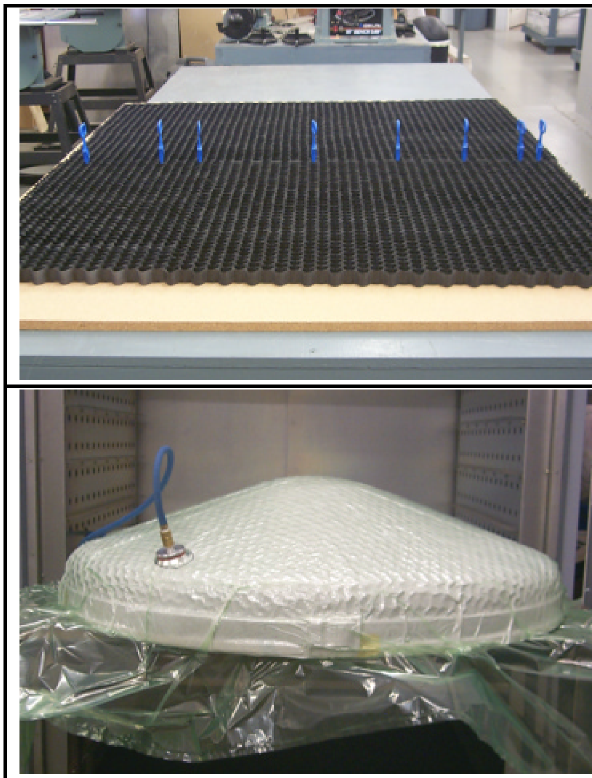


Fig. 2 – Standard H/C Production and Bonding

In addition to making large heatshields producible, the modular approach has other distinct advantages. First, it allows for concurrent manufacturing – the near-net molded modules can be produced prior to the arrival of the aeroshell structure. Second, it enhances the NDI process – the molded modules can be inspected from both faces and a defective unit can

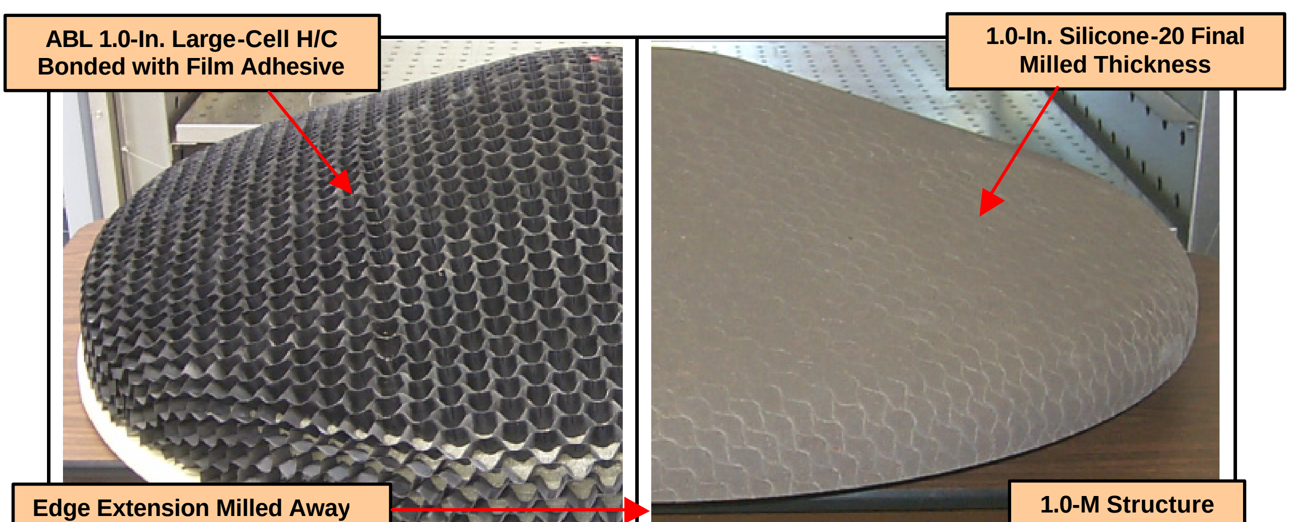


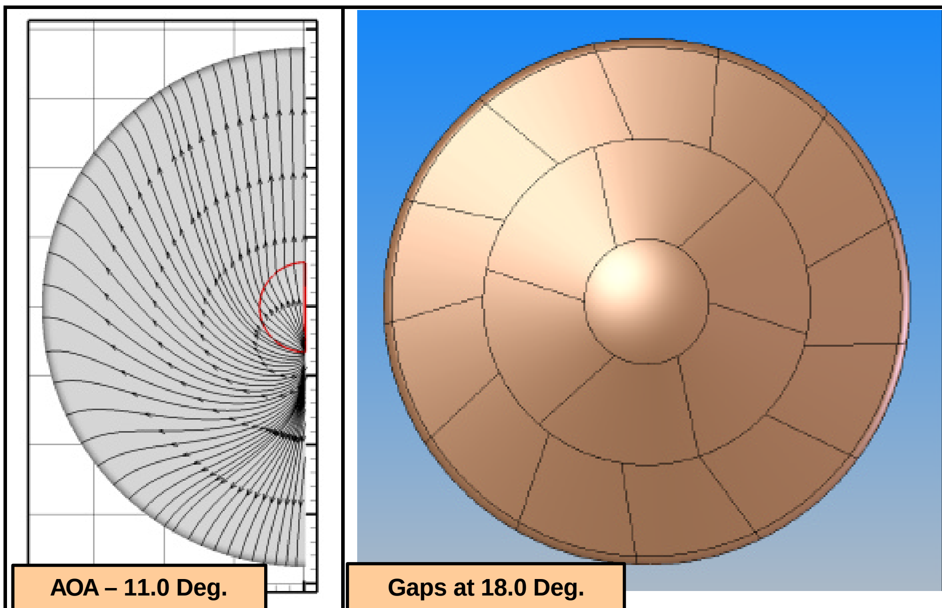
Fig. 3 – Ablative Heatshield Manufacturing by Standard Honeycomb Packing – 1.0 m Aeroshell

be discarded/replaced without loss of major investment. Third is that modular manufacturing opens the door for introduction of additional new technology in ablative heatshield systems – for example, it facilitates the use of a dual-layer ablator (dense robust top layer over a light-weight insulator of the same chemistry). Uniform D-L ablators are doable on a bench top, but difficult to near impossible to make *in-situ* directly on the aeroshell structure. Another advantage of significance is that modular production can make the installation of aerothermal sensors and heatshield performance sensors simpler and easier to accomplish.

3. Genesis of ABL's Modular Production

Interest in modular ablative heatshields started about six years ago. The ABL was contacted by NASA/JPL in 2005 and asked to provide information regarding how we could produce a large 4.5-m diameter aeroshell and heatshield for a future Mars mission. (At one point the diameter for this vehicle was even larger, at 5.5-m.) This was such a large aeroshell, likely using an ablator with a catalyzed resin system, that we decided the best way to make it would be by modular construction. The manufacturing plan that we devised and presented to JPL is briefly summarized in Fig. 4. We designed an elastomeric silicone heatshield with twenty individual H/C-packed ablator modules each having an area of about 10.0 ft^2 (0.93 m^2). The gap widths between modules would be precisely controlled by using spacers during module bonding. Then the gaps would be filled and packed with the same ablator compound as the 20 primary modules, followed by vacuum-bag oven curing. Consistent with what was shown in Fig. 1, we planned to orient the gaps at about 18.0-deg. or so depending on the vehicle's designed AOA during entry and the resulting analytical estimation of flowfield streamlines. Shown in the left side of Fig. 4 is a NASA/LaRC prediction of streamlines for a trajectory with 11.0-deg. AOA. In the right side of Fig. 4 are listed dimensions and mass for the lightweight and flexible ABL ablative material of 17.0 lb/ft^3 (0.27 g/cm^3).

ABL manufacturing for the ablator modules of Fig. 4 would use reusable precision molds to produce near-net modules of the designed shape and dimensions. Standard honeycomb would be pre-shaped by thermal treatment to assume the shape of the mold and then mechanically held in place at selected border regions to be later milled away. Fig. 5 shows a preliminary solid model for such a mold. The ablator would be packed and cured using this mold. In addition, the mold would provide precision reference points for the initial CNC milling of the ablator module. Fig. 5-C shows the cured and milled module lifted from the mold with bonded-on plastic eyes for easy handling. These eyes would be then milled away with surface overpack during the final milling step. (An alternate to eyes would be vacuum cups.)



20 Modules Total

Nosecap (1)
Area – 9.75 ft^2 / 0.906 m^2
Vol – 0.988 ft^3 / 0.0280 m^3
Mass – 16.8 lb / 7.62 kg

Inner Ring (6)
Area – 10.0 ft^2 / 0.929 m^2
Vol – 1.04 ft^3 / 0.295 m^3
Mass – 17.5 lb / 7.94 kg

Outer Ring (13)
Area – 9.74 ft^2 – 0.905 m^2
Vol – 0.988 ft^3 / 0.0280 m^3
Mass – 16.8 lb / 7.62 kg

Total Mass*
322.7 lb / 146.4 kg

***Silicone-17 Ablator**
17.0 lb/ft^3 / 0.27 g/cm^3
(high elongation)

Fig. 4 – ABL Preliminary Manufacturing Plan for the Heatshield of 4.5-m Mars EDL Vehicle (2005)

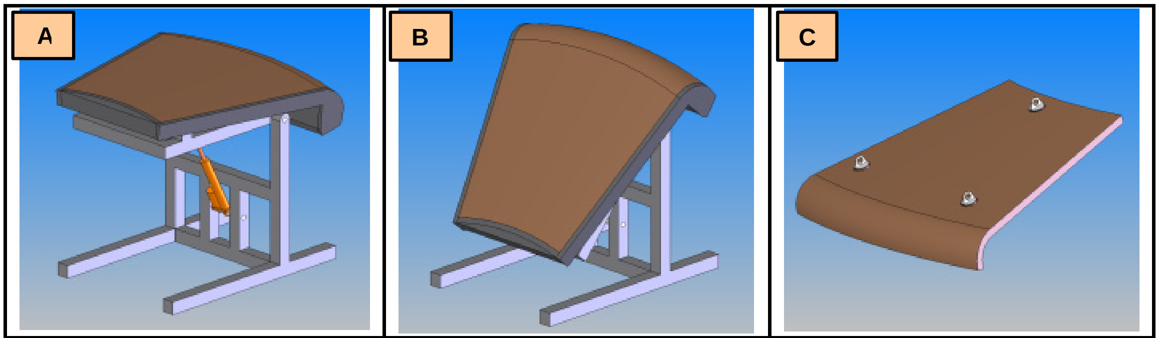


Fig. 5 – Conceptual Mold for Packing H/C to Make Ablative Flank Module of 5.0-m Aeroshell

4. Production of 1.0-m Modular Heatshield

The first modular heatshield from a honeycomb-packed ablator was produced by ABL in 2010. This was a phenolic-carbon ablator system with a density of 28.0 lb/ft^3 (0.45 g/cm^3). Reinforcement was a standard 1.0-in. large-cell H/C. The final ablator thickness was 1.0-in., but the ablator was packed with an overpack layer of approximately 0.25 in. Fig. 6-A shows the modular flank mold for this heatshield. It has removable sidewall extenders to contain ablator compound during packing. Fig. 6-B shows four flank modules in their molded, cured and milled state. Figs. 6-C and 6-D show the bonding of the five modules to the aeroshell composite structure using film adhesive and precision gap spacers. Accurately positioning the modules was done with the aid of a vacuum tool as shown in 6-D. Adhesive cure was done under vacuum bag pressure. Fig. 7 shows the resulting inter-module gaps. Such gaps have a keystone shape in cross section and this is done to provide a mechanical locking-in-place of the gap filler, which is the same ablator compound as used to form the modules. Packing of gap filler compound is shown in the photo of Fig. 7-D. Fig. 8-A shows the cured overpack ridges of the applied gap filler. Figs. 8-B and 8-C show the final 5-axis CNC milling of the heatshield's entire forebody surface. In Fig. 8-D the edge extension is shown being milled away to produce the final edge configuration of the heatshield.

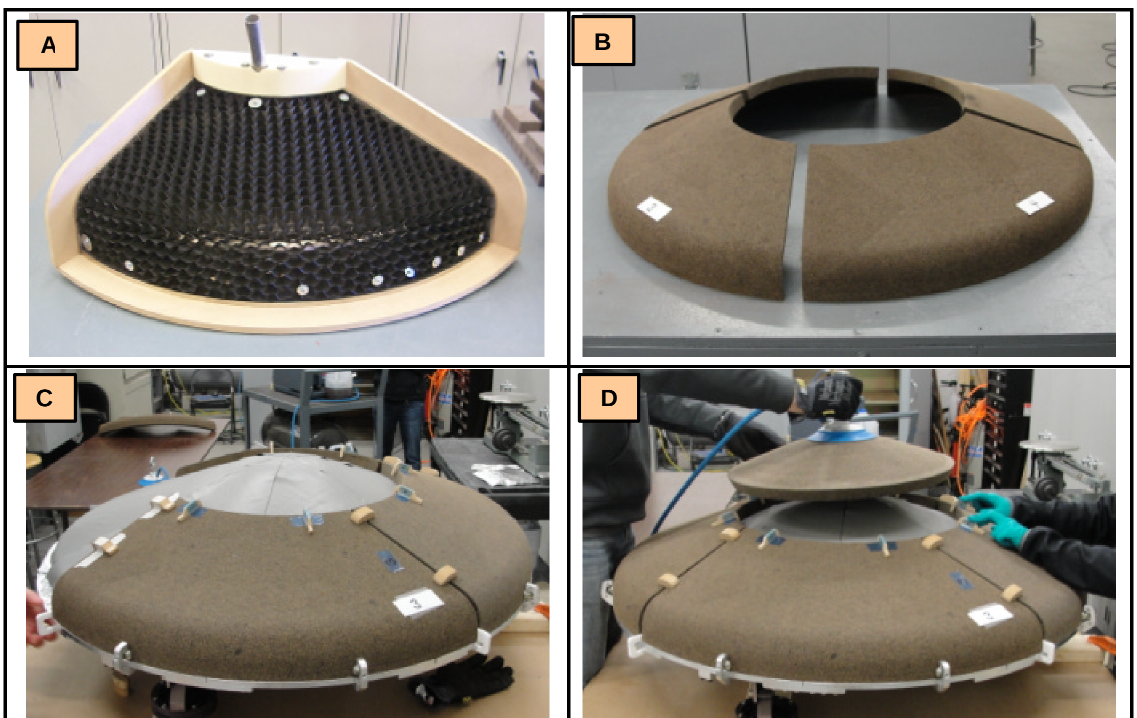


Fig. 6 – H/C Packed 1.0-m Ablator Modules Molded and Milled then Bonding to Structure

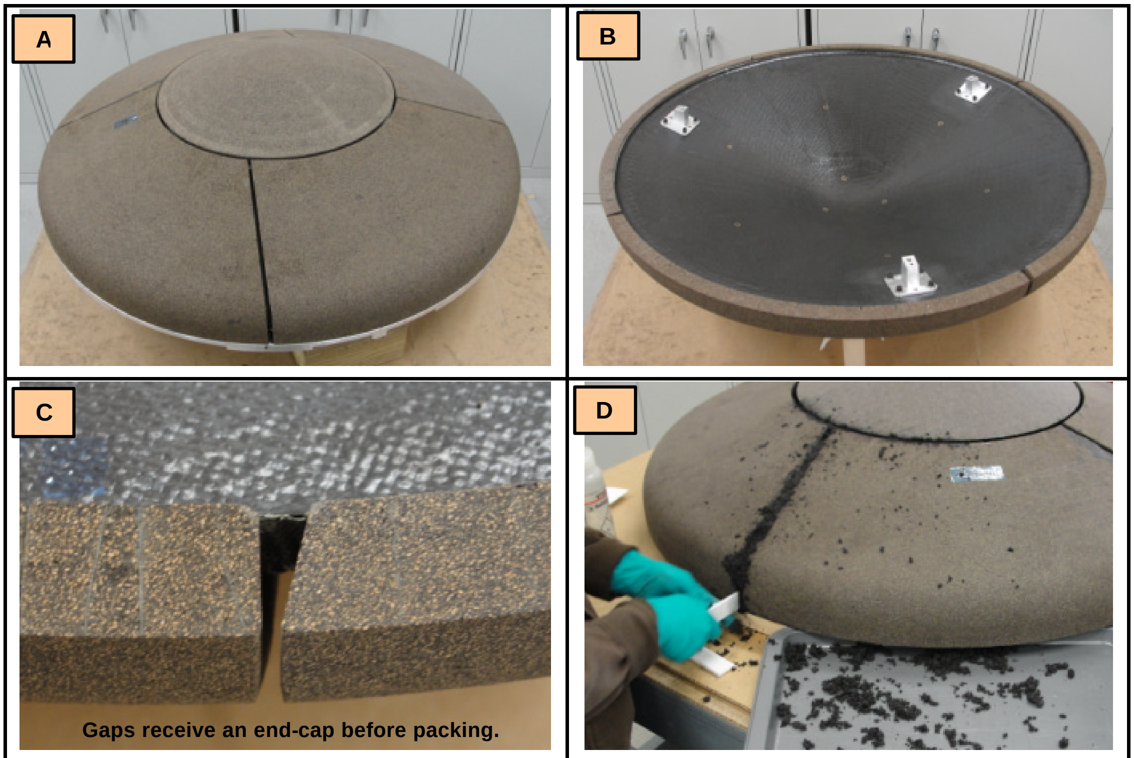


Fig. 7 – Intermodule Gaps with Keystone Profile and Filling Gaps with Same Ablator Compound

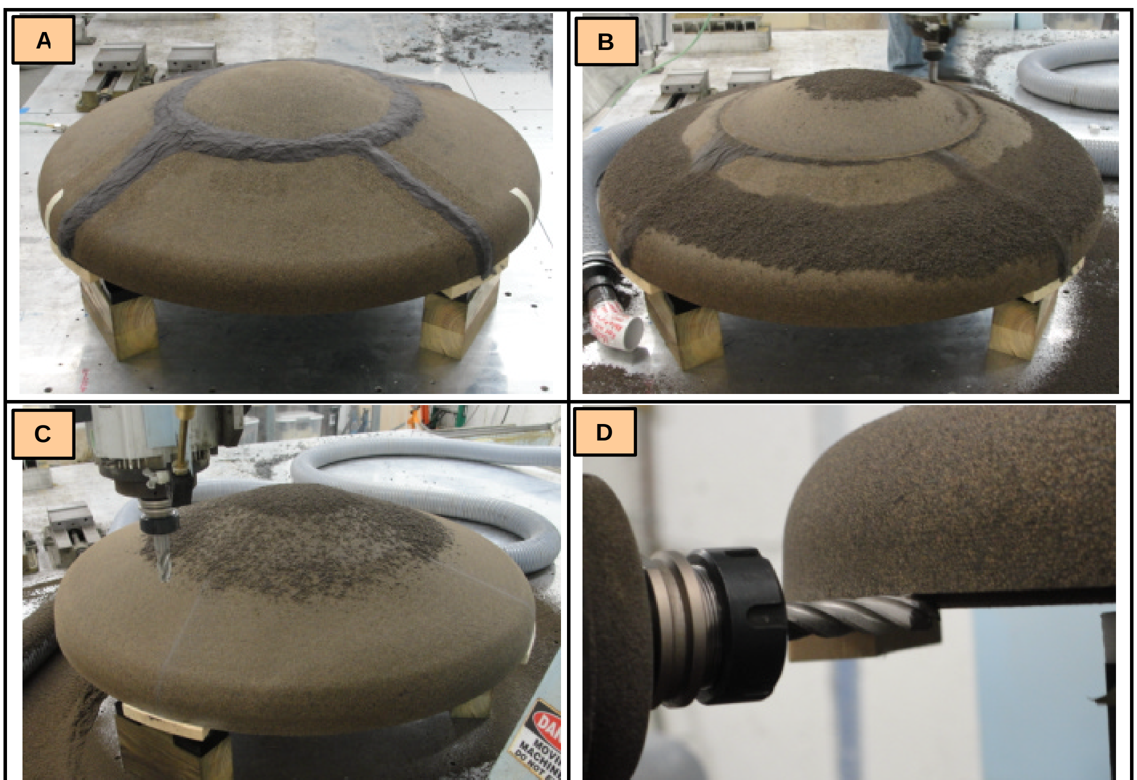


Fig.8 – 5-Axis CNC Milling Steps to Remove Excess Gap Filler, Overpack, and Edge Extension

Fig. 9 – Completed 1.0-m Modular Phenolic Heatshield Milled to Final "Flight Configuration"

5. Closure Discussion

The first manufacturing development and demonstration of a 1.0-m modular heatshield made with honeycomb-packed ablator was highly successful. The completed 1.0-m unit made from phenolic-carbon ablator is shown in Fig. 9. Visible in the photo are several of the packed ablator seams. The modular process, while it is not needed for small 1.0-m size units, can greatly improve the producibility of large heatshields of 4.0-m and 5.0-m size. Having completed our two 1.0-m units, the ABL is currently producing a 2.65-m modular heatshield that will be finished in 2011. Each of the modules on this heatshield is approximately 8.0 ft^2, nearly the same size as modules baselined by ABL in 2005 for the 5.0-m heatshield of Fig. 4. An important aspect of the demonstrated modular process is that the gap filler material is the same ablator compound as that of the molded modules. A different material was not required, such as RTV-560 used for gap filler on modular PICA heatshields. In a flight environment for the demonstrated phenolic heatshield, there would be no issue of differential recession caused by gap filler and thus no potential for interference heating effects. All regions of the heatshield would have a consistent ablation and insulation performance.

We completed two of the 1.0-m modular heatshields in 2010-11 in support of NASA's ISPT program. While these units could not be flight tested, we did the next best thing, and that was to test one of them at the Sandia Solar Tower facility to produce flight-like temperatures and thermal gradients. The primary purpose of the test was to validate thermostructural integrity of the aeroshell system. Fig. 10 shows the second 1.0-m unit in test at 150 W/cm^2 for 195 sec, a square-pulse exposure. Surface temperature in test was approximately 2000ºC and the bondline temperature peaked at 250ºC. Thermal performance of this phenolic aeroshell (the subject of a future paper) was very good with no indication of any issues related to heatshield debonding or structural delamination. Starting in July 2011, this tested unit is going through a posttest CT-scanning effort at DOE/LLNL, coordinated by NASA/ARC.

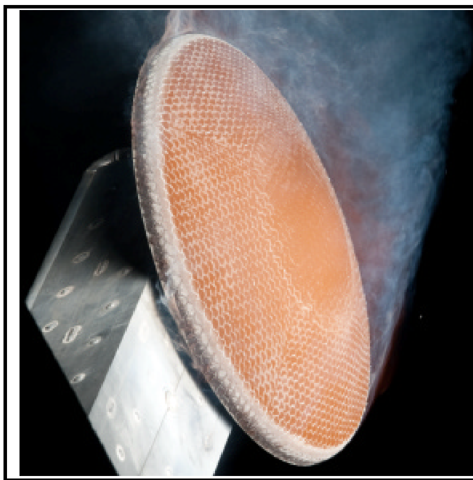


Fig. 10 – Modular Heatshield in Test

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